Special Topics on Basic EECS I
VLSI Devices
Lecture 17

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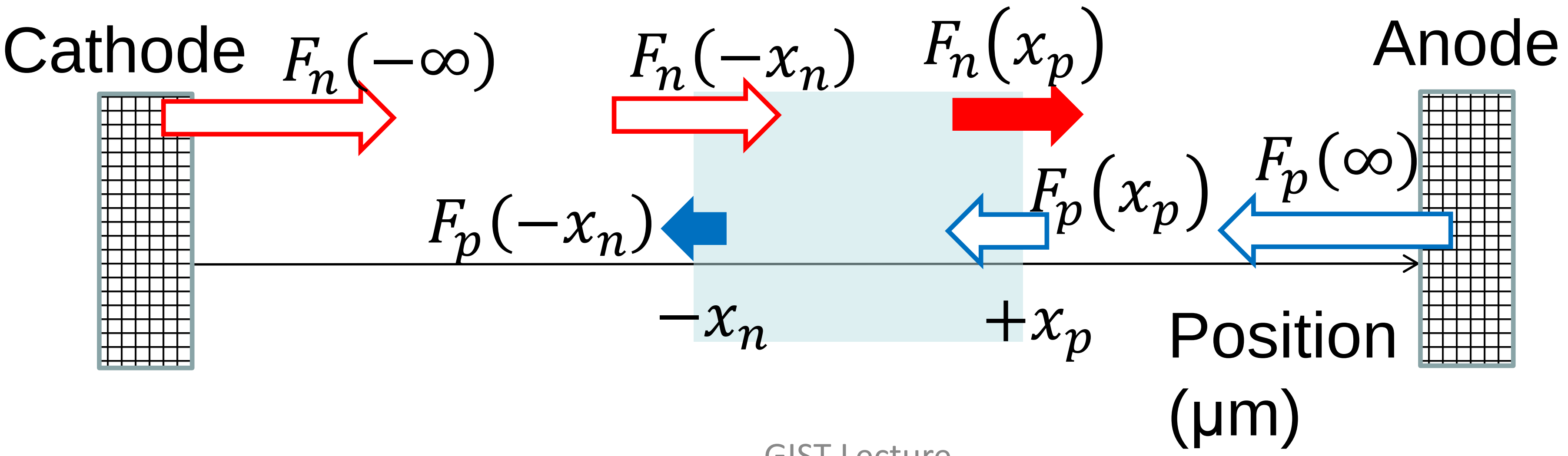
Recombination

- When the recombination in the depletion region is considered, we can find the following relation:

$$F_p(\infty) = F_n(-\infty) = F_n\left(x_p\right) + F_p(-x_n) + \int_{-x_n}^{x_p} [R(x) - G(x)]dx$$



Approximate expression

- We can estimate the upper bound.

$$\int_{-x_n}^{x_p} [R(x) - G(x)]dx < [R(x) - G(x)]_{maximum} \overbrace{(x_p + x_n)}^{W_d}$$

  - Assume that $R - G = CN_t \frac{np - n_i^2}{n + p + 2n_i}$ for the SRH centers.
  - Also, in the depletion region, $np = n_i^2 \exp \frac{V_{app}}{k_B T/q}$. (Why?)
  - Then, we have the maximum value

$$[R(x) - G(x)]_{maximum} = CN_t \frac{n_i}{2}\left(\exp \frac{V_{app}}{2\, k_B T/q} - 1\right)$$

$$= \frac{n_i}{2\tau_i}\left(\exp \frac{V_{app}}{2\, k_B T/q} - 1\right)$$

Current

- By using the previous results, the current can be obtained.

$$I_{total} = I_{diode} + I_{SC}$$ Taur, Eq. (2.138)

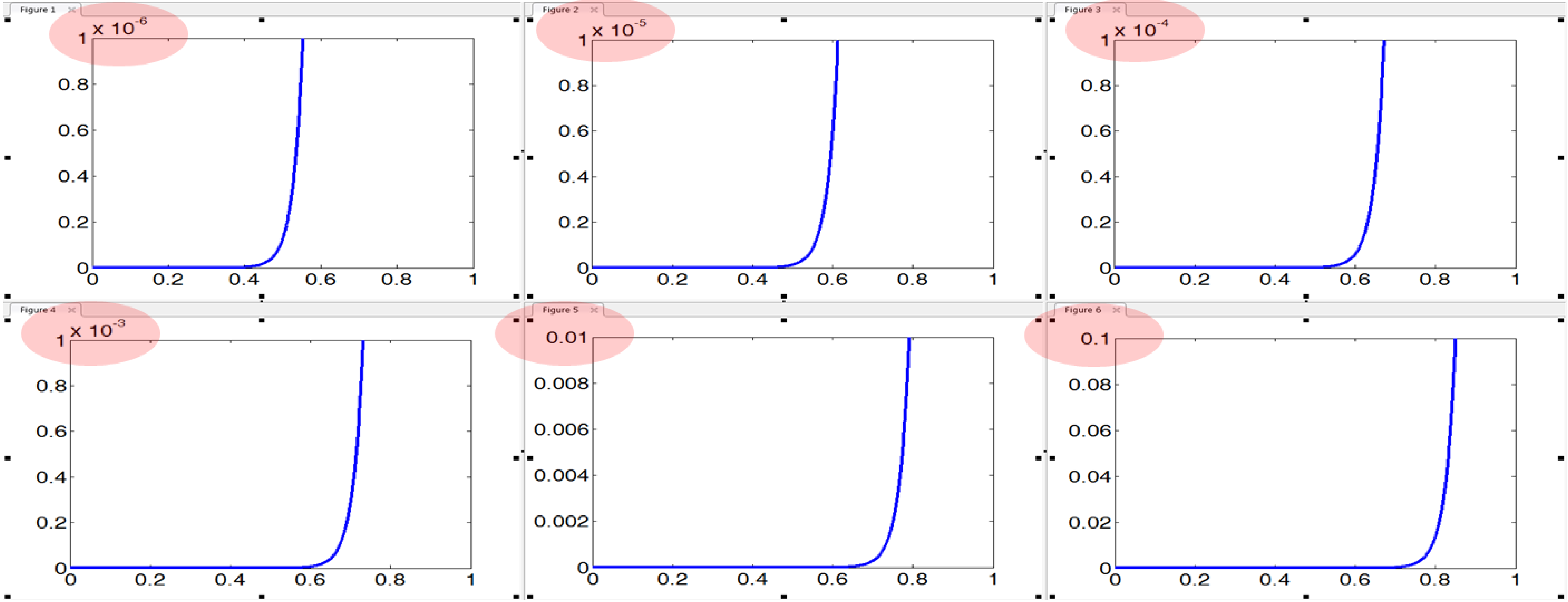
  - With the ideal factor, m, the forward diode current is often expressed in the form

$$I_{total} \sim \exp \frac{qV_{app}}{mk_BT}$$ Taur, Eq. (2.139)

  - When m is unity, the current is considered “ideal.”
  - The nonideality at small forward bias (m ~ 2) is caused by the space-charge-region current.

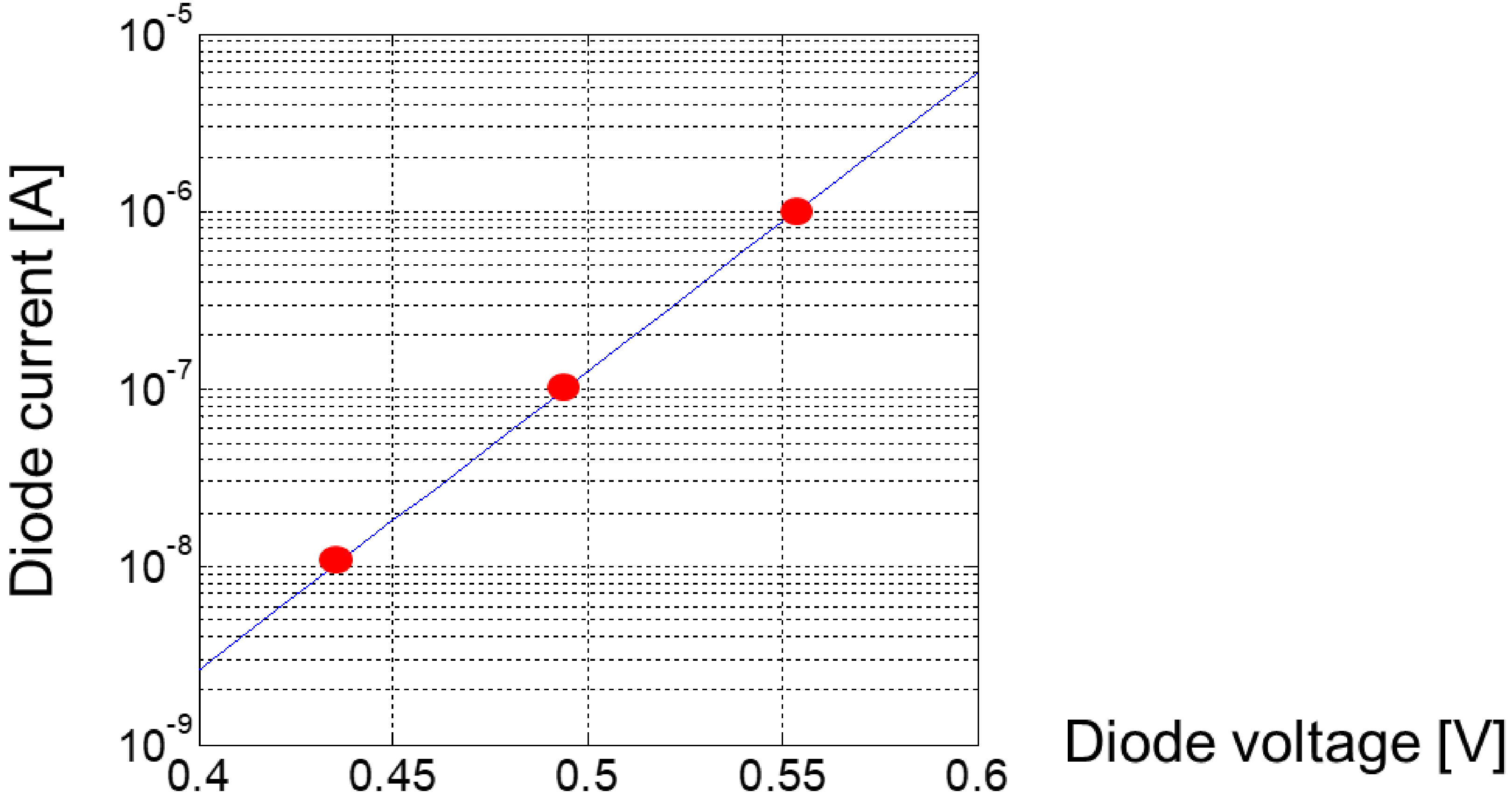
Diode IV curves

- A diode with $I_0 = 5 \times 10^{-16}\mathrm{A}$ (Only different y scales)



Important observation

- In order to obtain 10x higher current,
  - We must apply only 60 mV additionally. (300 K)



Short diode

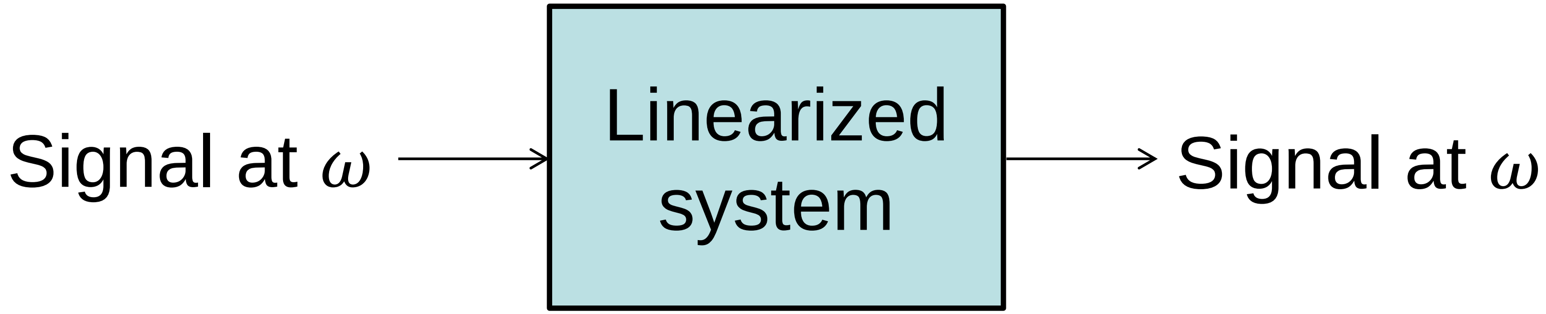
- Consider a case where p- and n-regions are shorter than the diffusion length.
  - Our previous solution: $n(x) = n_{p0}\left(\exp\frac{V_{app}}{k_B T/q} - 1\right)\exp\left(-\frac{x-x_p}{L_n}\right) + n_{p0}$
  - It assumes infinitely long p- and n-regions.
  - Opposite extreme:

$$n(x) = n_{p0}\left(\exp\frac{V_{app}}{k_B T/q} - 1\right)\left(1 - \frac{x - x_p}{W_p - x_p}\right) + n_{p0}$$

Linearized system

- Our device is nonlinear in general. However, we can *linearize* it,
  - When signals have small amplitudes.
  - Consider $y = \exp x$.
  - When $x = 24 + 12 \sin \omega t$, how does y look like?
  - When $x = 24 + 0.04 \sin \omega t$, how does y look like?
  - Can you justify the Taylor expansion?

$$y = \exp(x_0 + \delta x) = \exp x_0 \ \ (1 + \delta x\ )$$



Switching from OFF to ON

- It takes some time before the diode is turned on and reaches the steady state.
  - Charging up the depletion-layer capacitor
  - Filling up the p- and n-regions with excess minority carriers
- Similarly, when a diode is switched from the ON state to the OFF state, it takes some time before the diode is turned off.

Excessive minority carriers

- (The lightly doped side is often referred to as the *base* of the diode. The other one is called the *emitter*.)
  - Total excess minority-carrier charge per unit area

$$Q_B = -q\int_0^W (n_p - n_{p0})dx \qquad \text{Taur, Eq. (2.144)}$$

  - For a wide-base diode,

$$Q_B = J_n(x=0)\tau_n \qquad \text{Taur, Eq. (2.145)}$$

  - For a narrow-base diode,

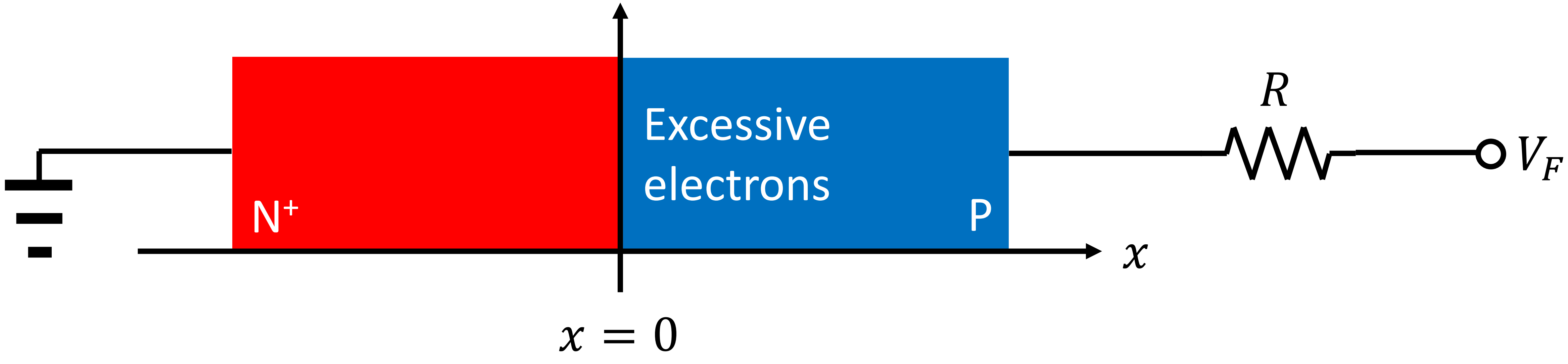
$$Q_B = J_n(x=0)t_B \qquad \text{Taur, Eq. (2.146)}$$

Base-transit time, $\frac{W^2}{2D_n}$

Discharging time of a forward-biased diode

- External voltage changes from V_F to V_R at $t = 0$. Assume that $|V_F|$ and $|V_F|$ are sufficiently higher than 1.0 V.
  - At $t < 0$,

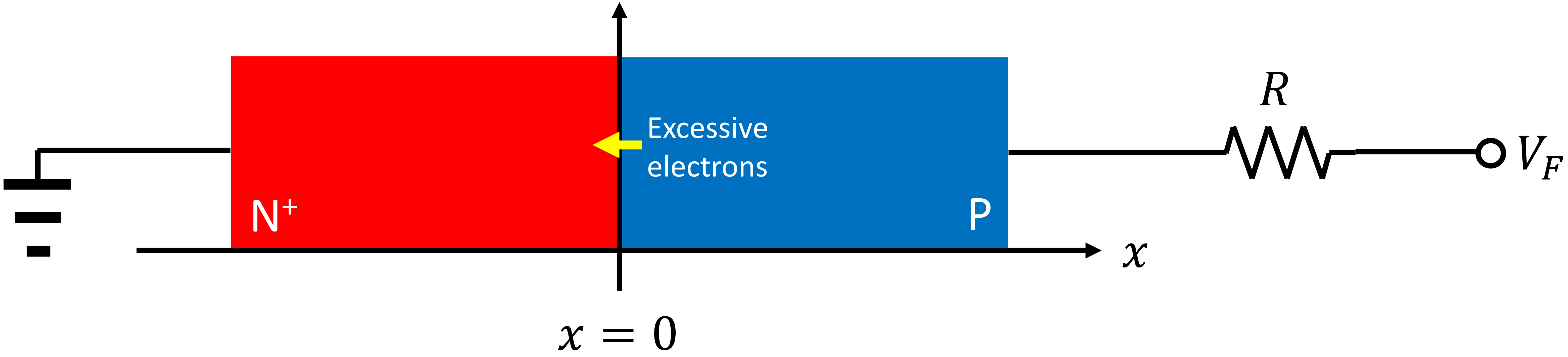
$$I \approx \frac{V_F}{R}$$



Reverse voltage of V_R

- Electrons at the edge of the depletion region are swept away by the electric field in the depletion region towards the n⁺ emitter at a saturated velocity.
  - The reverse current is limited by the external resistor,

$$I \approx \frac{V_R}{R} \text{ (Note that it is a negative number.)}$$



Later,

- The reverse current is limited by the diffusion of electrons instead of by the external resistor.
  - Finally, when all the excess electrons removed, the pn diode is completely off.

Thank you!